Supernova remnants

[1] The standard model

[a] SNRs evolution

[b] Expected X-ray emission and morphology

[2] Reality check

[a] A morphology zoo

[b] ...and a spectral mess

[3] Conclusions

Independently of the nature of the explosion
Four steps in SNR evolution

- Free expansion: In general does not last more than 300 years.
- Adiabatic expansion (Sedov-Taylor phase): lasts for $\approx$ 20,000 years.
- Radiative phase (Snow-plow): can last for up to 500,000 years.
- The remnant merges into the surrounding medium.

We describe SNR evolution using
three parameters:

- The initial energy of the explosion
- The density of the interstellar medium in which the shock wave is propagating
- The age of the remnant

Free expansion phase

Independently of the nature (massive-star core collapse or thermonuclear explosion of an accreting white dwarf) of the supernova, the shock wave propagating outward does so with no deceleration and the front shock propagates freely.

At this time, evolution is completely determined by E_0, the initial energy released in the medium (E_0 range from 0.5 to 1.5×10^{51} ergs).

Typical mass of material ejected: $M_{\rm ejected} \sim 1\ {\rm M}_\odot$
Typical initial velocity of the ejected shell: $v_{\rm ejected} \sim (7{-}12) \times 10^3\ {\rm km\,s^{-1}}$

Mass swept-up is negligible until the shock is at a radius of which depends on $M_{\rm ejected}$, and the density of the medium (n_1 (typical values of n_1 range from 0.1 to 5 cm^{-3}) and μ the mean mass per particle–

$$R_s = \left(\frac{3\, M_{\rm ejected}}{4\, \pi\, \mu\, n_1}\right)^{1/3} \tag{1}$$

If R_s in pc, $M_{\rm ejected}$ in ${\rm M}_\odot$and n_1 in cm^{-3}, this can be written as 2.55 pc $\left(\frac{M_{\rm ejected}}{n_1}\right)^{1/3}$ (total mass in the volume defined by R_s is equal to the total ejected mass).

$$t_f = 250 \text{ yrs}\, M_{\text{ejected}}^{5/6} \mathrm{n}_1^{-1/3} E_{51}^{-1/2}, \tag{2}$$

The "free-expansion" phase can last for about (200-350) years.

Then effects of the surrounding material are becoming importants: The evolution enters the second phase: the "Sedov-Taylor" phase.

Sedov-Taylor Phase or Adiabatic Phase of SNR Evolution

First work done during WWII (Taylor) Much of this work was re-derived independently (Sedov)
Realization that the problem of the expansion is "self-similar": Solutions can be *scaled* from the solutions at the shock front (or at any point for that matter).
Separate the variations in time and radius with a function depending only on the ratio of the radius and the radius at a given reference point (usually the radius at the shock) and the other being the value expected at that point of reference. This hypothesis simplifies greatly the description of the supernova evolution. The equations describing it are derived from conservation principles (mass, momentum and energy) across the shock - neglecting radiative losses.
Variables are ρ, v, P are the interstellar medium (ISM) density, velocity and pressure.

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial (r^2 v \rho)}{\partial r} = 0, \tag{3}$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r} + \frac{1}{\rho}\frac{\partial P}{\partial r} = 0, \tag{4}$$

$$\frac{\rho^\gamma}{P}\frac{d}{dt}\left(\frac{P}{\rho^\gamma}\right) = 0. \tag{5}$$

Boundaries conditions and self-similarity leads.

$$\rho_s = \frac{\gamma+1}{\gamma-1}\rho_1, \tag{6}$$

$$P_s = \frac{2\rho_1 V_s^2}{\gamma+1}, \tag{7}$$

$$\upsilon_s = \frac{2}{\gamma+1}V_s, \tag{8}$$

where ρ_1 (ρ_s) is the unperturbed ISM density (the density at the shock), P_s the pressure and V_s the velocity of the shock (note that υ_s is the velocity right behind the shock). The fundamental assumption of self-similar equations implies that if one writes:

$$\rho = \rho_s g(x),\ g(1) = 1, \tag{9}$$

$$P = P_s f(x),\ f(1) = 1, \tag{10}$$

$$\upsilon = V_s h(x),\ h(1) = \frac{2}{\gamma+1}, \tag{11}$$

where $x = r/R_s$ is the reduced radius at the shock, then

$$x(x-h)g' - xgh' = 2gh, \tag{12}$$

$$\frac{2(\gamma-1)}{(\gamma+1)^2}f' + gh'(h-x) = \frac{3}{2}gh, \tag{13}$$

$$gf'(h-x) - \gamma fg'(h-x) = 3fg. \tag{14}$$

For self-similar solutions to exist, one must require that ρ_s, P_s, V_s and R_s are linked by the following relations:

$$P_s = \frac{KE_0}{2\pi R_s^3}, \tag{15}$$

$$V_s = \left(\frac{(\gamma+1)KE_0}{4\pi\rho_1 R_s^3}\right)^{1/2} . \tag{16}$$

E_0 is the initial energy of the explosion. K is defined as the ratio of the thermal to the kinetic energy in the SNR and it is about 1.5.

If we integrate directly Equation (16) as a function of time, we find

$$R_s = \left[\frac{25(\gamma+1)KE_0}{16\pi\rho_1}\right]^{1/5} t^{2/5}. \tag{17}$$

We transform Equation (17) to express the radius of the shock as a function of quantities directly accessible to observers. Equation (17) becomes:

$$R_s = 12.4\,\mathrm{pc}\left(\frac{KE_{51}}{n_1}\right)^{1/5} t_4^{2/5}, \tag{18}$$

E_{51} is the initial energy of the explosion in units of 10^{51} ergs, n_1 the density of the pre-shock medium in cm^{-3} and t_4 the age of the SNR in units of 10^4 yrs. We can express the R_s as a function of the angular size (radius) of the object (θ in arcmin), the distance expressed in kpc and denoted $\mathrm{D_{kpc}}$ and the measured temperature across the remnant. the SNR in arc minutes and the distance to the object. We have

$$R_{\mathrm{pc}} \simeq\, 0.291\, D_{\mathrm{kpc}}\, \theta \tag{19}$$

Valid for the Sedov-Taylor. Can be seen as solutions of the evolution of the SNR in a homogeneous medium with energy losses neglected.

Radiative phase

As seen, the temperature drops as a steep function of radius. At one point the temperature drops below the threshold at which recombination of carbon and oxygen is dominant over ionization (T $\sim$ 0.1 keV). The SNR starts to cool rapidly.

Age for the SNR at that time?
Depends on model for cooling functions assumed in addition to explosion energy and density.
Ages of SNR can be anywhere between 17,000 and more than 25,000 years (assuming an average explosion energy and a standard density.

After a time depending on the pressure of the ambient interstellar gas and the two quantities E_{51} and n_1, the SNR merges with the surrounding material, the emission in X-rays becomes negligible compared to the optical emission.

Merging phase

This phase is the fourth and last phase of the SNR evolution.

The total energy of the explosion has been dissipated in the ISM. One estimate of the maximum lifetime of a SNR before its complete dissipation into the ISM is given by:

$$t_{\rm max} = 7\ \times 10^6\,{\rm yr}\,E_{51}^{0.32}\,n_1^{0.34} P_{-4}^{-0.70}, \tag{20}$$

where P_{-4} is $10^{-4}\ \times P_0$ and P_0 is the pressure of the ISM. The shock wave is not strong enough to sustain itself. The expansion comes almost to a halt as the remnant merges with the surrounding medium. No emission is seen. The ISM contains now a larger amount of heavy elements which have been created prior to and in the explosion.

X-ray emission from SNRs

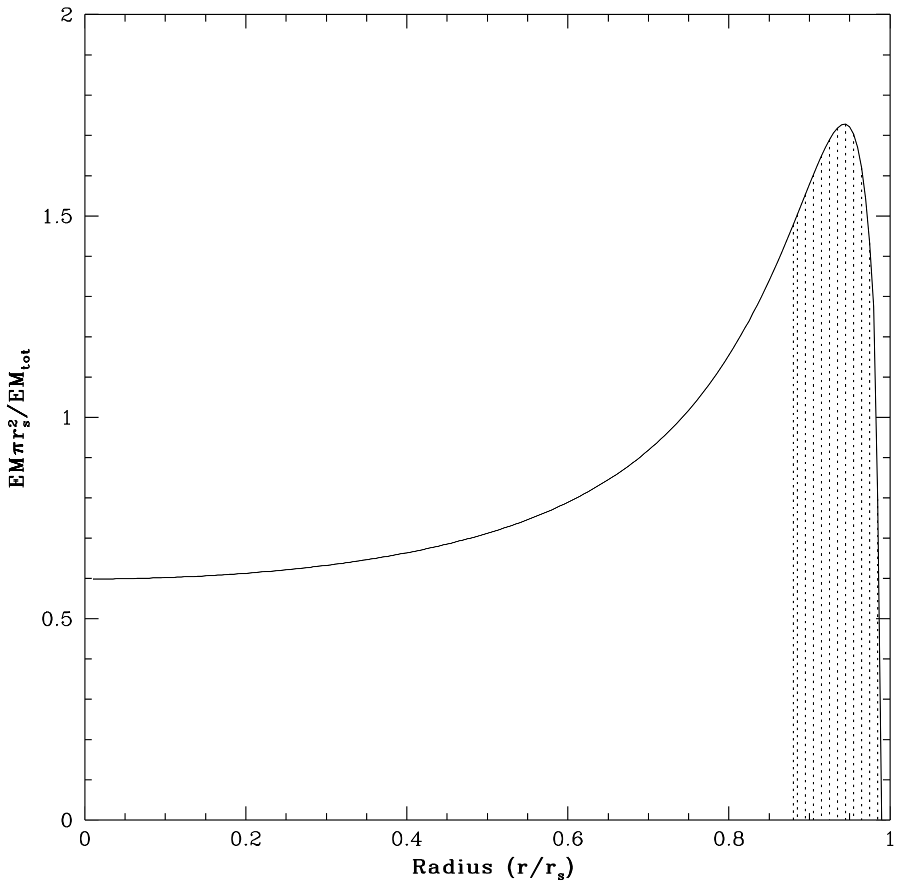


Figure 1: **Surface brightness variation as a function of the SNR radius.**

X-ray emission from SNRs

X-ray production (thermal)

- Gas in the ISM heated by the blast-wave (Collisional ionization)
- Ejecta heated by the reverse shock (Same as above - varying abundances)
- Surface emission from the compact object (Black body)

X-ray production (non thermal)

- Synchrotron radiation (Power law or more sophisticated)
- Fermi acceleration at the shock (Power law)

Contributions to the thermal emission

Precomputed models

- Lines:
  - Direct excitation
  - Dielectronic recombination
  - Innershell ionization (Auger)
  - Radiative recombination
- Continuum
  - Bremsstrahlung
  - Radiative recombination

Non Equilibrium Ionization problems

If $(\mathrm{age})_{SNR} \ll (\mathrm{time})_{eq}$, ionization state of elements is not the one corresponding to the temperature.

To characterize this departure from equilibrium
Ionization Timescale: nt

Information provided by the X-ray spectrum

- Bremsstrahlung Continuum $\Longrightarrow$ Temperature
- Lines in the Spectrum $\Longrightarrow$ Ionization Timescale
- Lines relative strength $\Longrightarrow$ Elemental abundances

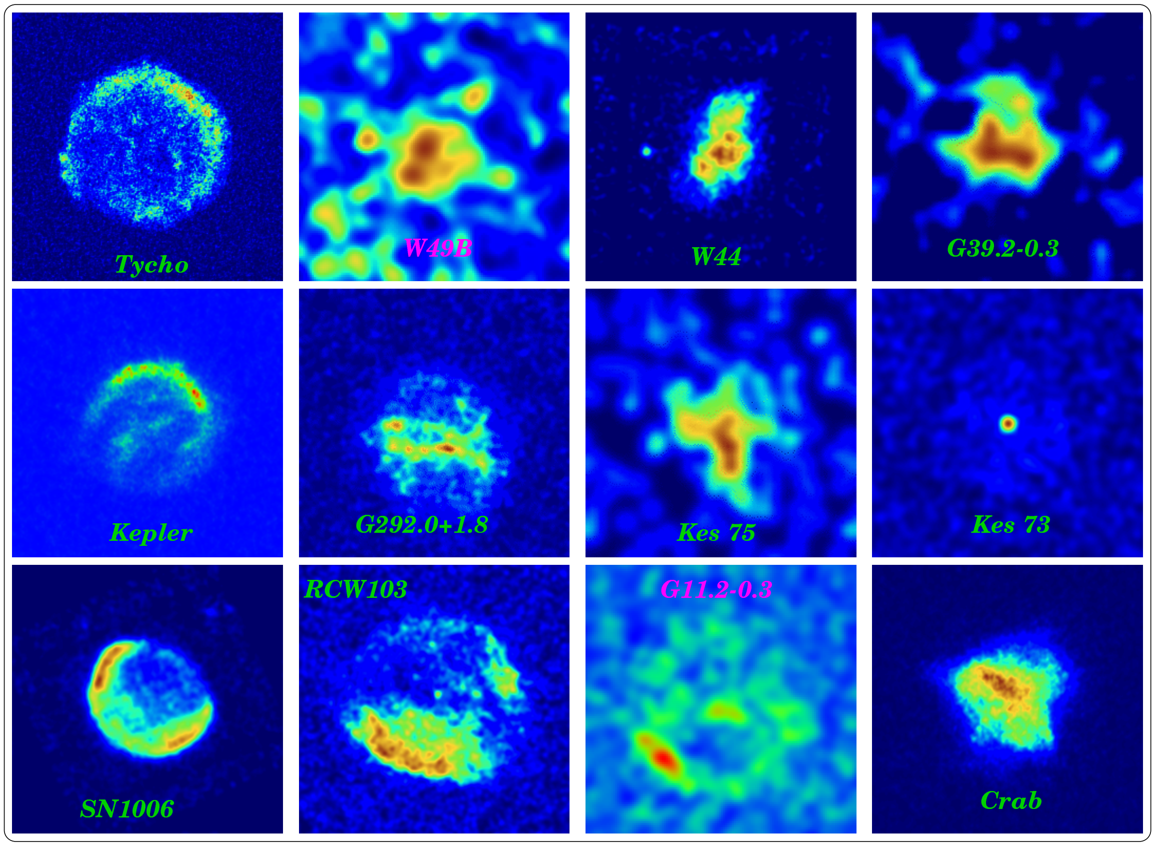


Figure 2: **Examples of different X-ray images of SNRs (Data from *Einstein* IPC & HRI)**

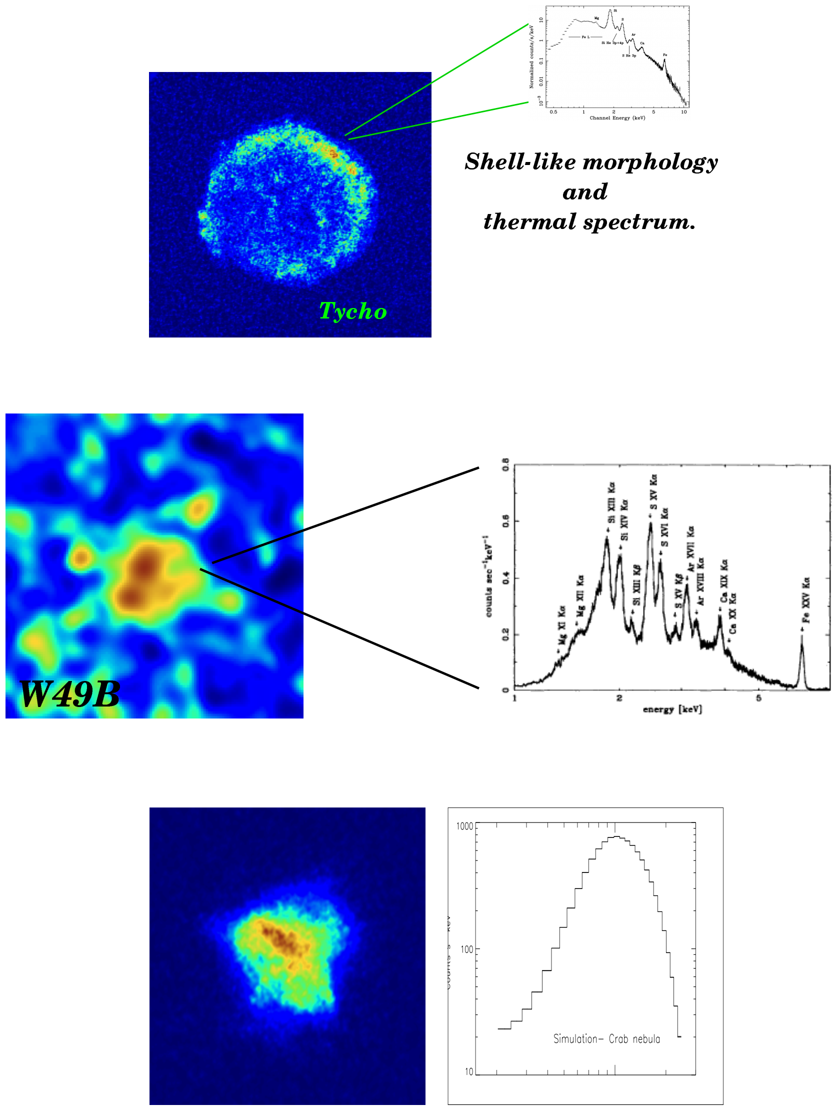
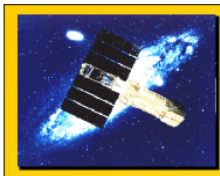
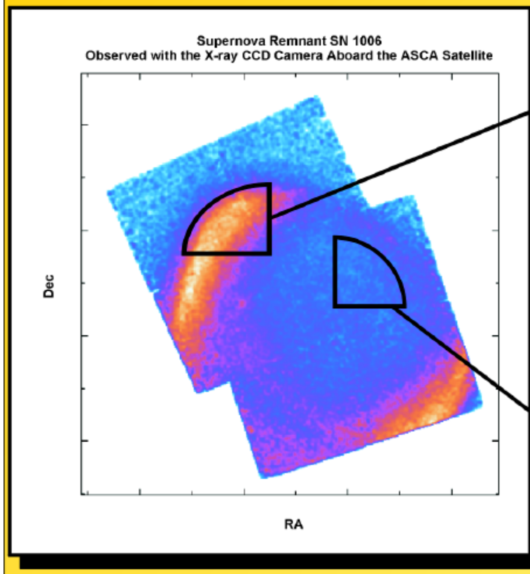
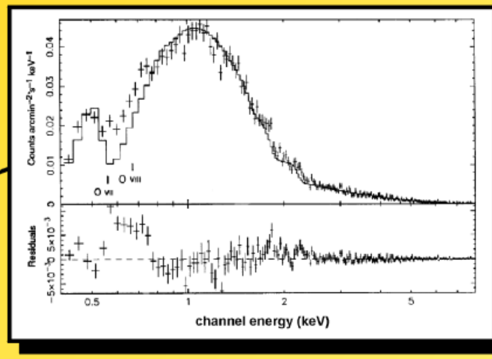


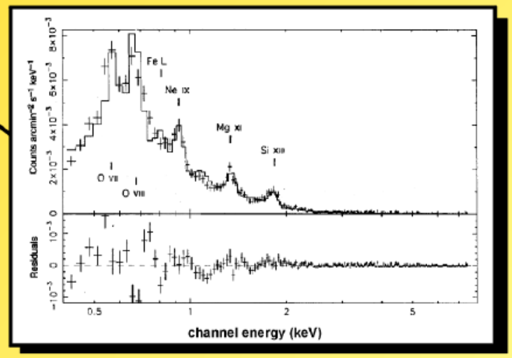
Figure 3: **Examples of different X-ray spectra of some of the remnants shown in the previous graph (Except when noted: data from *ASCA* SIS)**



Cosmic Ray Production in Supernova Remnants







ASCA observations of the supernova remnant SN 1006 have revealed the first strong observational evidence for the production of cosmic rays in the shock wave of a supernova remnant. These results come from the detection of non-thermal synchrotron radiation from two oppositely located regions in the rapidly expanding supernova remnant. The remainder of the supernova remnant, in contrast, produces thermal X-ray emission showing Oxygen, Neon, Magnesium, Silicon, Sulfur, and Iron line emission.

(Koyama, Petre, Gotthelf, Hwang, Matsuura, Ozaki, & Holt, Nature, 378, 255, 1995)

Solutions to the morphology problem

[a] Column density variation

[b] Cloud evaporation model (with/without thermal conduction)

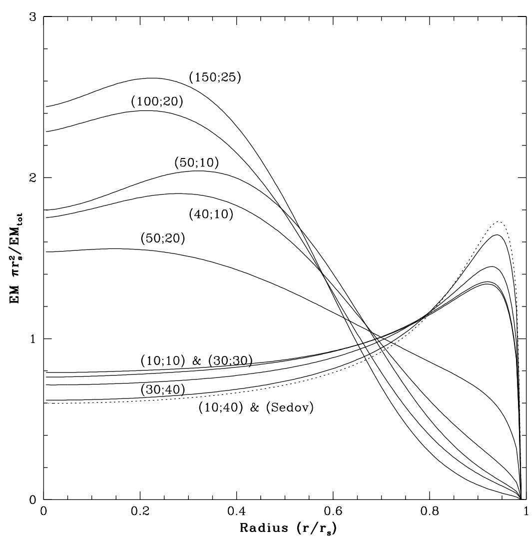


Figure 4: **Variations of the normalized surface brightness as a function of the normalized radius of the SNR. This variations have been computed for a wide range of values of C and τ. The normalization is done so that the total emissivity is fixed. The dotted line shows the expected curve in the case of the standard Sedov-Taylor model.**

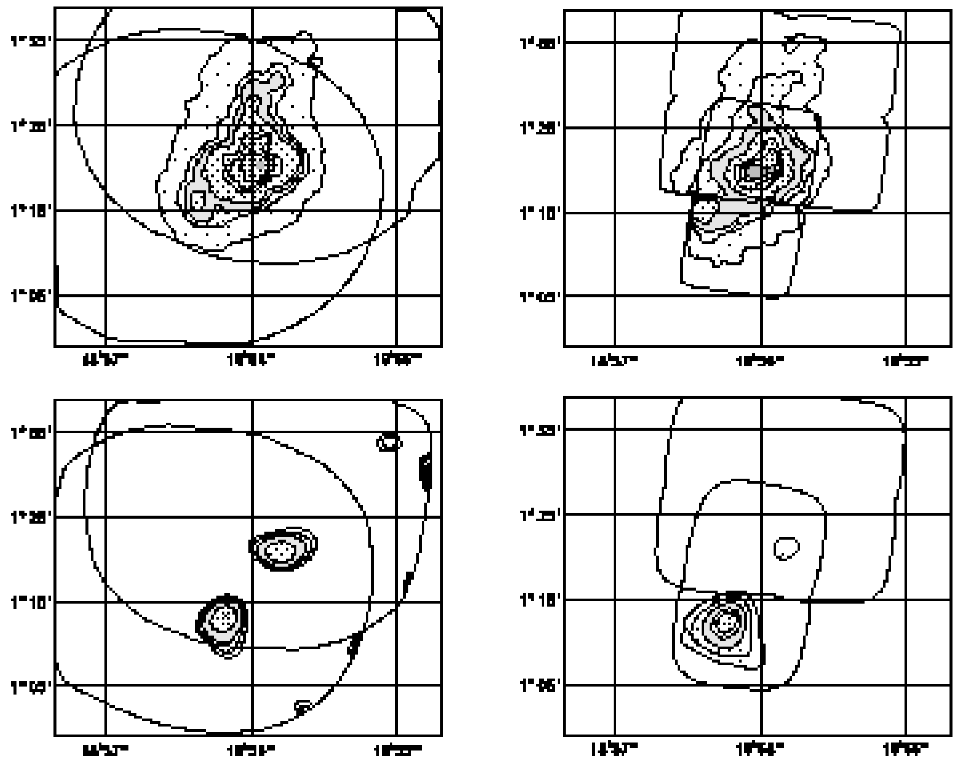


Figure 5: *ASCA* **GIS and SIS images for W44 at low (below 4 keV) and high (above 4 keV) energy**

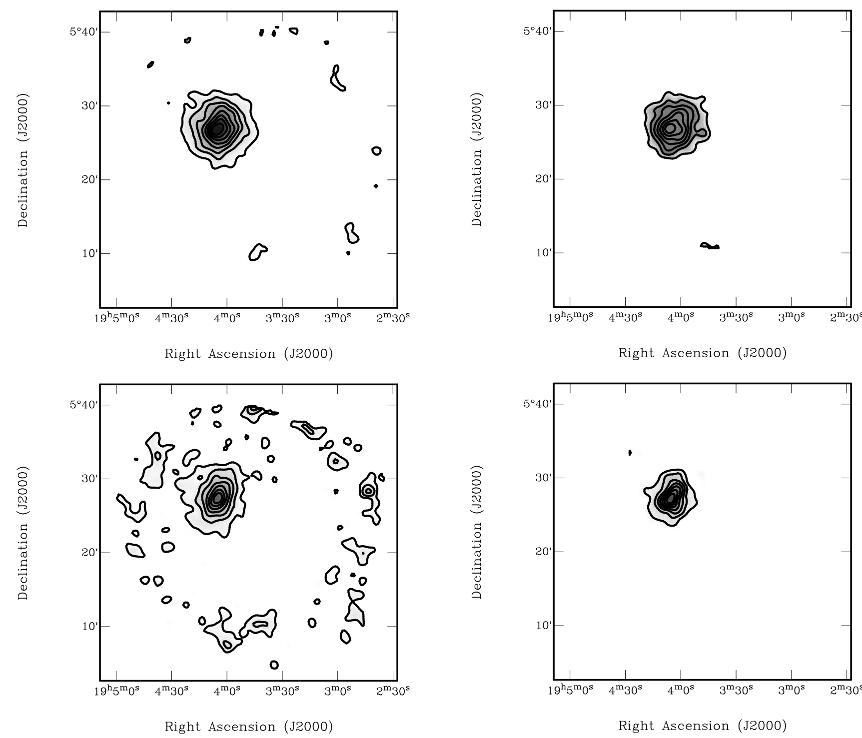


Figure 6: *ASCA* **X-ray images of the SNR G39.2−0.3 at low and high energy (top: 0.5–3.0 keV; bottom: $\gtrsim$ 3.0 keV) for the GIS (left) and the SIS (right). Contour values are linearly spaced from 30% to 90% of the peak surface brightness in each map. Peak/background values are top: 2.58/0.12; bottom: 1.72/0.08 for the GIS and top: 2.57/0.12; bottom: 1.74/0.19 for the SIS, where all values are quoted in units of 10^{-3}counts s^{-1} arcmin^{-2}.**